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A Prototype Flight-Deck Airflow Hazard Visualization System

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ABSTRACT

Airflow hazards such as turbulence, vortices, or low-level wind shear can pose a threat to landing aircraft and are especially dangerous to helicopters. Because pilots usually cannot see airflow, they may be unaware of the extent of the hazard. We have developed a prototype airflow hazard visual display for use in helicopter cockpits to alleviate this problem. We report on the results of a preliminary usability study of our airflow hazard visualization system in helicopter-shipboard operations.

INTRODUCTION

Many aircraft accidents each year are caused by encounters with unseen airflow hazards near the ground, such as vortices, downdrafts, low level wind shear, microbursts, or turbulence from surrounding vegetation or structures near the landing site. These hazards can be dangerous even to airliners; there have been hundreds of fatalities in the United States in the last two decades attributable to airliner encounters with microbursts and low level wind shear alone [1], [2]. However, helicopters are especially vulnerable to airflow hazards because they often have to operate in confined spaces and under operationally stressful conditions (such as emergency search and rescue, military or shipboard operations).

Airflow hazards are hard to detect simply because air is invisible. Its flow pattern is undetectable by pilots on a landing approach unless the air happens to pick up dust, smoke or other aerosols that are visible to the human eye. Being thus unable to directly see a factor of potentially great importance to them, pilots learn to use their intuition concerning airflow over obstacles near the takeoff or landing site, and they learn to pick up visual cues from the surrounding area. These methods are inadequate, however, as airflow-related accidents still occur.

Providing helicopter pilots with an augmented-reality display visualizing local airflow hazards may be of significant benefit. However, the form such a visualization might take, and whether it does indeed provide a benefit, had not been studied before our experiment.

We recruited experienced military and civilian helicopter pilots for a preliminary usability study to evaluate a prototype augmented-reality visualization system. The study had two goals: first, to assess the efficacy of presenting airflow data in flight; and second, to obtain expert feedback on sample presentations of hazard indicators to refine our design choices.

We chose to focus our research on helicopter-shipboard operations due to the inherently demanding environment replete with airwake hazards. We created a simulation of the view from a helicopter cockpit during the approach to land on a moving ship, and added virtual-reality airflow hazard indicators to the display.

The study addressed the optimal way to provide critical safety information to the pilot, what level of detail to provide, whether to display specific aerodynamic causes or potential effects only, and how to safely and effectively shift the locus of attention during a high-workload task. Three-dimensional visual cues, with varying shape, color, transparency, texture, depth cueing, and use of motion, depicting regions of hazardous airflow, were developed and presented to the pilots.

The study results indicated that such a visualization system could be of significant value in improving safety during critical takeoff and landing operations, and also gave clear indications of the best design choices in producing the hazard visual cues.

HAZARD DETECTION ARCHITECTURE

A complete onboard airflow hazard detection system would consist of three major components: sensors; classification and analysis; and display (human interface). Our research addresses the display stage, but we describe the others here to illustrate the problem in context.

SENSORS/DETECTION

Recent technological advances in sensor technology, especially Doppler lidar [3], PIV (Particle Image Velocimetry) [4], and forward-looking microwave radar, offer the potential for aircraft-based sensors which can gather large amounts of airflow data in real-time. There are currently available commercial systems utilizing this technology to detect moderate-scale airflow disturbances such as microbursts and windshear [5], [6], [7]. Current research into airflow detection techniques such as lidar is promising; it is believed that within a few years hardware capable of being mounted on an aircraft will be able to reliably scan the area a few hundred feet ahead of the aircraft and sample air particle vector velocities at one-foot intervals or less [8]. With the development of such devices, onboard detection systems that can convey detailed, specific information about airflow hazards to pilots in real-time become a possibility.

CLASSIFICATION/ANALYSIS

This area concerns the development of algorithms to input the particle positions and vector velocities, other variables such as density altitude, aircraft gross weight, and power available; to compute the locations of the areas of flow which may produce a hazard to this particular aircraft on this particular day; and to output the three-dimensional coordinates of the hazard location in real-time.

DISPLAY TO THE PILOT (USER INTERFACE)

Given the airflow data and the known hazard areas, the problem then becomes to organize this vast amount of data, describing millions of particles swirling in different directions, and present it to the pilot in a manner that does not interfere with the primary task of operating the aircraft safely. An interface is required that can present potentially large amounts of data to the pilot in a non-intrusive yet comprehensive manner in real-time.

MOTIVATION FOR VISUAL INTERFACE USABILITY STUDY

Since an airflow hazard detection system generates a large amount of disparate data that must be organized and presented to a human operating a complex machine in a high-workload environment, an efficient method of human-machine communication is required. The human visual system has the highest bandwidth of all the senses. It can process gigabytes of data in real-time and organize it into patterns that the brain can use to draw conclusions and act very quickly. Beyond this general observation about the efficacy of visual input, we also note that the operation of landing an aircraft is an essentially visual operation, even if the flight itself is made under instrument weather conditions; the pilot looks at least at the instruments, and finally always at the landing site. It therefore makes sense to organize the airflow data into some type of visual display.

As with any type of user interface, usability evaluation is important to ensure that the display most efficiently supports the human operator's performance. Given the demanding environment and the relatively small population of highly trained pilots, it is especially critical to conduct a usability study before designing an airflow hazard display system.

SHIPBOARD HELICOPTER OPERATIONS

Although the need to detect airflow hazards exists for all pilots in all aircraft, for our research we chose to focus on helicopter operations, and specifically on Navy shipboard rotorcraft operations, to which the Navy refers as the "Dynamic Interface." There were several reasons for this choice.

Helicopters are especially vulnerable to airflow disturbances; first, by the nature of the aerodynamic forces involved, and second, because helicopters are often called upon to operate into and out of confined areas or areas that naturally have disturbed airflow. For example, emergency search and rescue may have to operate in mountainous areas and small clearings surrounded by vegetation and cliffs where the winds are always high. Helicopters also must land on urban rooftops, offshore oil platforms, or on the decks of ships. A device for detecting airflow hazards therefore has a special utility for helicopter operations.

Operating a helicopter off a moving aircraft carrier is one of the most demanding tasks a helicopter pilot can face [9]. Because the ship is moving, its superstructure will always generate an airwake consisting of vortices and other unseen hazards. In addition, high sea states may cause extreme ship motion, and low visibility may degrade visual cues. The pilot must maneuver the helicopter within very tight tolerances under adverse conditions. It is a task that demands the utmost concentration and skill from the pilot. A system that can deliver even an incremental amount of assistance to the pilot in this high-demand environment could have a significant impact on safety.

Helicopter accidents and incidents that occur each year range from fatal accidents to incidents such as "tunnel strikes" (when a rotor blade strikes the fuselage of the helicopter). There have been approximately 120 tunnel strikes since 1960, causing damage ranging from $50-$75K to over $1M [8]. When analysis of these accidents and incidents is performed, the conclusion is frequently that they were due to unseen airflow hazards such as vortices, downdrafts, hot exhaust plumes, or wind shear, where the pilot and ground crew were initially unaware of the danger and the pilot was unable to react in time. Presenting the appropriate information to the pilot or flight deck air boss in advance of the hazard encounter could reduce or prevent these types of accidents in the future.

Finally, because shipboard rotorcraft operations are such a demanding environment, the area is very well studied. The Navy has compiled significant amounts of data from shipboard flight tests, wind tunnel tests, and computational fluid dynamics computations studying the airflow around moving ships of all types, and how the airwake changes when helicopters of different makes and models land on the ships. Utilizing the data from these extensive tests and computational studies, the Navy develops operational envelopes listing allowable wind conditions for many ship-rotorcraft combinations [10]. However, the envelopes are of necessity (for safety reasons) relatively narrow, and convey fairly limited information, basically a go/no-go decision. The envelopes do not state which safety considerations caused a particular operational limit, thus limiting the information available to the pilot. On the other hand, accidents and incidents occur during operations within the envelope every year. On occasion, during the post-accident analysis, the flight test engineers can point to existing airwake data to show that the accident was caused by disturbed airflow over a portion of the deck. In other words, the information that could have prevented the accident was known, but it had not been communicated to the pilot. Thus as Navy flight test engineers seek ways to increase fleet safety, this problem is ripe for solution.

The current method of communicating this information to the pilots consists of operational envelopes for each ship-rotorcraft combination [Figure 1].

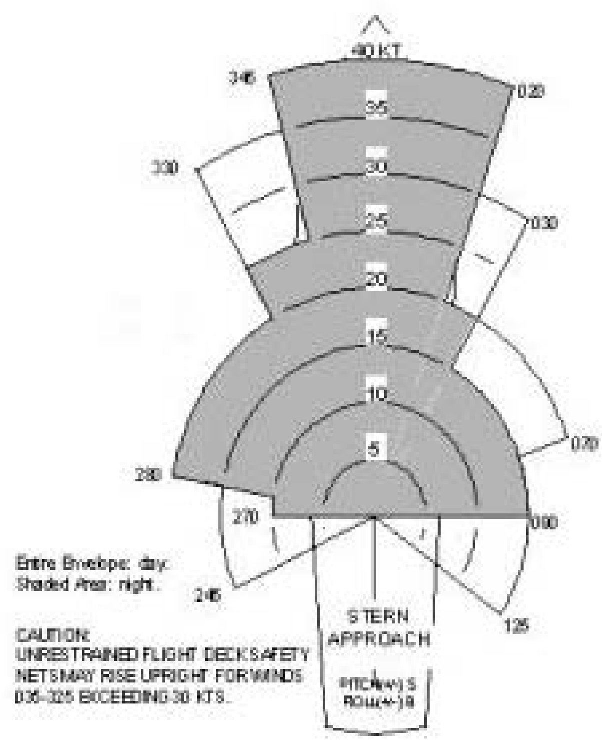

Figure 1. Ship-rotorcraft operational envelope

The envelope depicts the allowable wind speeds and directions that a given helicopter is allowed to land on a particular ship. It is necessarily conservative, as the envelope has to include all flight conditions and all fleet pilot skill levels. The envelopes limit allowable landing conditions significantly; however, even with this cautious approach, accidents due to airflow hazards still occur. In one recent example, a helicopter was damaged when starting up on shipboard, even though the winds were within the allowable starting envelope. Another helicopter was operating upwind of the first, and this configuration caused hazardous airflow to be present at the downwind spot [8]. There was knowledge of this problem from the Navy flight testing program; however, the envelopes cannot portray every combination of aircraft location on a ship that may have many helicopters and aircraft in operation at the same time.

EXPERIMENT DESIGN

During potentially hazardous conditions, high winds, low visibility, or extreme ship motion, the pilot's attention will naturally be focused outside during the critical landing moments; he or she will not want to look down at a cockpit instrument display. In designing our experiment, we assumed pilots would prefer an augmented-reality hazard visualization display (as was verified during the usability study). However, the head-up display must be carefully designed not to distract from the key shipboard visual cues, which may be degraded during a challenging nighttime or poor-weather landing on a ship. Studies have shown that head-up displays with superimposed symbology may on occasion cause performance problems due to attentional capture by the perceptual grouping of the superimposed symbols [11]. "Scene-linked" head-up displays, or displays where there is no differential motion between the superimposed symbology and the outside scene, can avoid this type of distraction. For this reason we decided to develop a head-up display where the hazard indicator is three-dimensional and appears to be physically part of the world.

RAPID PROTOTYPE PHASE

We first constructed a horizontal prototype (a relatively full-featured simulation of the interface with no underlying functionality) [12] of an augmented-reality hazard visualization system that included many different types of hazard indicators. The usability study on the horizontal prototype had two main goals: first, to determine whether presenting airflow hazard data to helicopter pilots would be helpful to them; and second, to obtain expert feedback on the presentation of sample hazard indicators, from which we could refine our design choices.

We decided to perform interactive prototyping [12], a technique where the prototype is altered on the fly as the test user comments on its effectiveness. This enabled us to rapidly modify the design and obtain feedback on multiple variations in a single session.

PLATFORM SELECTION FOR RAPID PROTOTYPE

The next task was to identify the best tool for creating a relatively realistic, three-dimensional visual simulation of the helicopter pilot's view out the cockpit windscreen during the final approach to a shipboard landing. The tool was required to support rapid prototyping, 3D modeling, and simple animation. It was especially important that we be able to create new hazard visualizations within minutes, as we were hoping to get feedback from the study participants and implement their suggestions during the session so as to tighten the feedback loop.

Consultation with Navy flight test engineers provided detailed descriptions of what a landing approach should look like. Additionally, we were provided with an extremely detailed 3D CAD model of a Spruance-class destroyer (DD 963). An ideal prototype platform would be able to use this data to render a realistic approach.

Three approaches were considered for the prototype software platform: a low cost, off-the-shelf flight simulator; a 3D animation system; and a 3D CAD tool.

The Microsoft Flight Simulator was considered because it offered the possibility of the pilots being able to use a joystick, and potentially the opportunity to alter the visual hazard display without affecting the flight simulation. However, there was no convenient interface for importing the existing ship model into MS Flight Simulator.

We also investigated various 3D animation systems such as WildTangent, VRML, and Flash. However, although these systems could handle the animation well, the overhead for changing hazard indicators was considerable, essentially comparable to working in a programming language. (Actual programming languages, such as Java, were ruled out for the same reason.)

The CAD modeling tool we selected, Rhino3D, offered rapid construction and alteration of the prototype scenarios and easy access to the ship model data. It was very easy and quick to create many different types of hazard indicators and modify their shape, location, color, texture, and transparency. Although not a flight simulator, the CAD program allowed us to simulate the final approach to landing by rotating and zooming the model of the ship with the hazard indicator displayed above it.

METHODOLOGY

We recruited three highly experienced (>1700 hours) helicopter pilots and flight test engineers, all with shipboard landing experience. Each session with a participant pilot consisted of a one-and-one-half-hour interview with the pilot in front of a projection screen. All sessions were videotaped. Two experimenters conducted the session, one operating the computer and the other interviewing the pilot and taking notes.

The operator-experimenter used the Rhino3D CAD program to display on the projection screen a model of the ship (DD 963), with a hazard indicator displayed on the ship's deck where hazardous airwake might be found. The operator manually simulated a helicopter's view of an approach to landing on shipboard as the pilot watched and commented. A wide selection of different types of hazard indicators were stored in layers in Rhino3D, so that features could be selectively turned on and off by the operator [Figure 2]. The features that were varied in the hazard indicator included shape, location, color, texture, transparency, depth cueing, and motion.

Feedback was solicited from the pilot. If the pilot suggested a change, the operator implemented it on the fly and the pilot was asked to judge whether the change was an improvement. The experimenter asked both specific and open-ended questions throughout the interview designed to elicit the pilots' expertise.

Using the pilots' responses, we attempted to assess the efficacy of presenting airflow data in flight, and to select the most efficacious (as judged by the pilots) visual presentation for the hazard indicator.

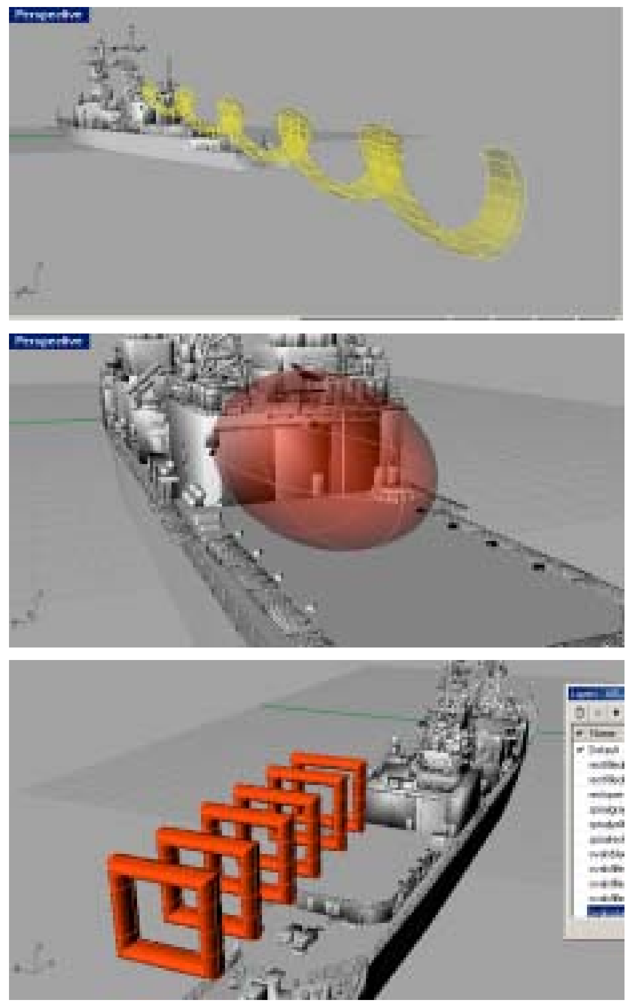

Figure 2. Hazard indicators in Rhino3D

PARTICIPANTS

In choosing participants, we sought pilots with a great deal of helicopter experience and, ideally, experience with shipboard landings of large military helicopters. Finding pilots with the requisite domain-specific knowledge was challenging. The final test group for the prototype consisted of two military pilots and one experienced civilian helicopter pilot:

Participant 1: Navy helicopter test pilot, 2000 hours of flight time, 17 years experience.

Participant 2: Navy helicopter flight test engineer, 4000 hours of helicopter simulator time, 100 hours of flight time, 17 years experience with shipboard helicopter flight tests.

Participant 3: Civilian helicopter flight instructor, 1740 hours of flight time, 3 years experience.

RESULTS

Results of the usability study on the rapid prototype were encouraging, but in some respects surprising as to the types of display features pilots found helpful. All participants said they liked the system and would use it if it were installed on their aircraft. As they viewed the interface, the pilots repeatedly stated that they wanted such a hazard visualization tool.

As to the type of visualization, the strongest overriding principle that emerged from this experiment is that helicopter pilots are using all their attention to focus on the extremely demanding task of landing on a moving ship deck, perhaps under low visibility conditions or at night, and the hazard indicator must not distract from that focus. To that end, the participants favored much simpler imagery than we would have expected.

The pilots strongly rejected the use of flow visualization indicators, and especially of motion to indicate flow. Given the manner in which fixed-wing pilots look for natural flow indicators such as dust devils near the runway, smoke plumes, wind-blown vegetation etc., we had anticipated that helicopter pilots would prefer a dynamic flow visualization, capable of indicating the direction and velocity of particles in the hazardous region. However, the participants exhibited resistance to such a design. All participants, even while reiterating their desire for 3D hazard visualization, stated that motion was distracting during the approach and particularly during the critical moments near touchdown. A static visualization, even supplying less information, was strongly preferred over a dynamic hazard indicator. That is, the participants sought a real-time decision support tool, not an airflow analysis tool.

Below we describe the hazard display parameters that were varied in the prototype usability test, and the results obtained for each.

COLOR

We showed hazard indicators in single and in multiple hues, using colors spanning the spectrum. All pilots preferred single-color hazard indicators, and indeed, preferred only two colors for the final system: yellow for caution and red for danger. Yellow, according to the participants, should indicate an airflow hazard that could necessitate strong pilot input to stay safe, but where the aircraft should maintain controllability. Red should indicate danger, an airflow hazard that would likely be beyond the limits of the aircraft and would put its controllability in question.

We were surprised to find the pilots unanimous on the point that a hazard indicator should be rendered in a single color (either red or yellow). Multiple-color hazard indicators were considered distracting and confusing. When the experimenters pointed out that a vortex core could have very strong winds but the outer portion of the vortex might not be as hazardous, so that a two-color indicator with a red core and a yellow mantle might be useful, the pilots all disagreed, saying the red vortex core would be difficult to see or to locate correctly in a three-dimensional object. In addition to the overall view that the display would be confusing, a concern was also expressed that a two-color indicator could tempt a pilot to venture into the yellow mantle while attempting to skirt the red core. That is, the two-color indicator was thought to potentially support an incorrect decision to land in dangerous conditions.

TRANSPARENCY

While holding other variables constant, we varied the transparency of the displayed hazard indicator from 20% to 80% (according to the Rhino software controls). This test was repeated for a range of objects. The pilots preferred an average transparency near 70%. While desiring a hazard indicator sufficiently opaque to come to the pilot's attention, participants noted the critical need for the pilot to be able to see visual cues on the ship behind the hazard indicator.

DEPTH CUES

We displayed hazard indicators that hovered above the deck and cast no shadow, and others that had a colored shadow projected onto the deck directly below the indicator. Of those with shadows, some had a connecting vertical line from the indicator to the deck shadow. All of the pilots preferred shadows below objects, stating that they helped the pilot to localize the 3D indicator in space. Pilot #1 said shadows alone might be sufficient for a shipboard hazard warning system: "just paint the deck red if I need to wave off." Pilot #2 liked the idea of a connecting line between the hazard indicator and the deck. No participant wanted tick marks or numeric information floating with the hazard indicators. Again, they preferred to keep it simple; the purpose is to let the pilot see the location and approximate severity of a hazard, not to help them measure or analyze it.

TEXTURE

We displayed hazard indicators having a series of arrows textured onto their partially transparent surface, to indicate the direction of airflow in that hazardous area, and asked pilots to compare them to indicators without the texture. Pilots #1 and #2 did not want the extra detail, saying it could be confusing or distracting. Pilot #3 suggested striping as a possible symbology, reminiscent of the yellow and black caution tape that is a common symbol to most Americans.

SHAPE

We asked the pilots to comment on the effect of varying the shape of the hazard indicator, such as rectilinear transparent boxes, cloud shapes with rounded corners, spirals, rings both round and rectangular. The rectilinear and cloud shapes were favored over all others. Again, a preference for simplicity was displayed. One of the pilots pointed out that the floating rings looked a little bit like the HUD symbology for the "highway in the sky" [13], perhaps beckoning the pilot to fly into the rings, the exact opposite of the intended action! This comment made clear the need to research all HUD symbology so as to avoid conflicts with existing symbology or commonly accepted designs.

MOTION

There was a strong consensus that motion in the display, particularly fast motion, was distracting. Pilot #1 (the participant with the most experience landing on shipboard in actual hazardous conditions) said the visual indicators should absolutely not use motion at all. It was distracting, and in the worst case could induce vertigo, especially at night or in low-visibility situations. The pilot stated that if the indicators had to change their position in real-time to indicate a change in the location of the hazard, they should move smoothly, and attention should be paid to the edges to make sure no flashing or other video artifacts appear that might distract the pilot from the task of landing. This pilot also stated that the indicators should fade in and out gradually in response to changing hazard conditions (unless the pilot turned them on or off). A sudden appearance of a hazard indicator, where there had been none, could be startling and potentially dangerous. Likewise any rapid motion or disappearance out of the corner of the pilot's eye during the landing could be distracting and potentially dangerous. Pilot #2 concurred that there should be no motion in the hazard indicators. Pilot #3, the civilian pilot, stated that *slow* motion on the surface of the indicator could conceivably be helpful to give an indication of which way the airflow was moving within, but that in general, fast motion could be distracting and dangerous.

AUDIO

Some existing hazard warning systems for commercial aircraft use audible warnings, e.g. a bell or voice. Participants in our study were asked whether they would judge an audio indicator to be helpful or distracting. The consensus was against using audio. Pilots #1 and #2 were clear that they did not want the hazard indicator to have any audio component. Pilot #3 conjectured that a limited audio, such as a soothing female voice, might be helpful under certain limited conditions.

GENERAL CONSIDERATIONS

Other comments the pilots made were that the indicator should appear at the 180-degree point, the point in the approach where the pilot is abeam the intended landing spot facing downwind. The indicators should then either turn off as the wheels cross the deck, or remain on throughout the landing. For yellow (caution indicated, but controllable) conditions, it was thought potentially helpful to leave the hazard indicator on display, as the pilot might choose to fly into the indicated area (the "curtain"). Numeric indicators representing airflow speed were not preferred; the pilots stated that they wouldn't have the time to read numbers as they approached the landing spot. All of the pilots preferred an idealized representation rather than exact visualization of airflow, again in the interest of keeping the display simple. One pilot suggested just painting the deck or the landing spot red or yellow. It was also suggested that more detailed options might be useful at the start of the approach. Perhaps a helicopter silhouette on the deck, or wind arrows or airflow lines, could be selected by the pilot at that point, fading to a simpler version as the pilot flew closer. It was also pointed out that it was important for the system to be credible, with no false positives or negatives. Finally, it was critical that the pilot be able to turn the system on and off, and that a vernier control be present to adjust the brightness of the display based on the ambient light.

CONCLUSIONS AND FUTURE WORK

A preliminary usability study of an airflow hazard visualization system for helicopter pilots landing on board a moving ship confirmed that pilots would use such a system if it were available on their aircraft. They expressed a need to know more about airwake hazards and a desire to have the information presented to them in the cockpit during the landing approach. The preference was for a head-up display with "scene-linked" indicators vs. an instrument panel display.

The pilots indicated that any airflow hazard symbology should present the minimum critical information such as location of the hazard and whether it was a warning (yellow) or danger (red). There was no desire for detailed quantitative information or even qualitative information such as type of hazard such as vortex, downdraft, turbulence, wind shear, etc. In other words, what the pilots are looking for is a decision support system, not a scientific visualization system, and any future work in this area should be done with this kept in mind. They want to be shown the effects – e.g. hazards to aircraft – and not causes – e.g. this is a vortex caused by the wind curling up and over the deck edge with downdrafts of up to 400 ft/minute. Extensive detail, motion, complex shapes, too many colors, were all considered too distracting and possibly dangerous in the high-demand environment of shipboard helicopter operations. Preference was strongly given to static rather than dynamic indicators. Concerns were expressed over distractions such as motion inducing vertigo, confusing symbology causing doubt in the pilot's mind, etc. Nevertheless, there was a clear desire to have such a system in the cockpit.

Further work is indicated and currently the author is conducting a flight simulation study using a preferred set of hazard indicators. Airflow data and ship and helicopter aerodynamic models have been loaded into a high-fidelity rotorcraft flight simulator [14] and scenarios have been created where airflow hazards are known to be present near various landing spots on shipboard. A visual hazard indicator system has been developed and implemented, and integrated into the display system of the simulator. Experienced helicopter pilots with shipboard landing experience have been recruited to fly multiple approaches to a moving aircraft carrier under extreme wind and turbulence conditions, both with and without the visual hazard display. Data is being gathered both subjectively by having the pilots fill out questionnaires about the hazard visualization system, and objectively by measuring flight path deviations, control surface motion and pilot workload, landing dispersion, and vertical speed at touchdown.

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